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The Influence of the Changing Geomagnetic Field on Cosmic Ray Measurements

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Cosmic ray cutoff rigidities, numerically computed using geomagnetic field coefficients, are frequently used as an ordering parameter for cosmic radiation data. Examples of the use of cutoff rigidities as an ordering parameter include latitude surveys, long-term galactic radiation studies, and solar cosmic ray event analyses.

1. Background

Cosmic ray measurements have been made on a world wide basis for the past sixty years, and since that time the cosmic ray community has been a prime abuser of the available and various geomagnetic field models. The first extensive measurements of the cosmic radiation intensity as a function of latitude were made on ship. The data were originally ordered by geographic latitude; later geomagnetic latitude was found to be a slightly better ordering parameter. Since that time various geomagnetic parameters have been used to order cosmic radiation intensity measurements such as those made at different locations using the same detector (e.g., a latitude survey) or those made by similar detectors located at vastly different geomagnetic locations (e.g. during geomagnetic storms or solar cosmic ray ground-level enhancements). Approximately 30 years ago the geomagnetic cutoff rigidity was found to be an extremely appropriate unit for the ordering of many cosmic ray measurements, and this quantity continues to be used today.

Cosmic ray experimenters have exactly the same problems that magnetic experimenters have. They have biases, offsets, and noise in their data; they have stability problems and long term drifts in their instrumentation, and to compare recent measurements with very early measurements, they have problems in normalizing the data acquired using vastly different instruments. When various data sets did not appear to "fit" to expectations, the geomagnetic parameter used to order the measurements was often a convenient explanation for any inconsistencies. In fact, until the past decade, cosmic ray scientists assumed that when the geomagnetic modelers derived a really "good" magnetic field model it would be used to solve many of the persistent problems in cosmic ray physics.

2. Geomagnetic Cutoff Rigidity

Probably the biggest problem in the ordering of cosmic ray intensity data using the geomagnetic field as an ordering parameter is the determination of the geomagnetic cutoff rigidity at the measurement location. The cutoff rigidity is a concept which

describes the geomagnetic shielding provided by the earth's magnetic field against the arrival of charged cosmic ray particles from outside the magnetosphere. Rigidity is a specialized term, momentum per unit charge; it is a unit independent of particle species or nuclear composition which can be converted to an energy for any specified charged nuclei.

The cutoff rigidity is defined as the lowest rigidity a charged particle can possess and still arrive at a specific point on the earth's surface. Strictly speaking, the cutoff rigidity of any geographic location is a function of the zenith and azimuth angles of arrival, the altitude of the detection location, and the geomagnetic conditions at the time of the measurement. Because of this complexity, calculated cutoff rigidities are usually determined for the vertical direction at the measurement location. In using a quiescent geomagnetic field model, calculations yield a vertical cutoff rigidity on the earth's surface of 13 to 18 GV in the magnetic equatorial regions and essentially zero near the magnetic poles. Therefore a cosmic ray detector operating in the earth's polar regions would measure the entire cosmic ray spectrum (limited only by atmospheric absorption) whereas a cosmic ray detector operating in the earth's equatorial regions would measure only those cosmic ray particles above the geomagnetic cutoff rigidity.

The method for making a rigorous determination of the cutoff rigidity by calculating the trajectories of particles as they traverse the earth's magnetic field has long been advocated (STÖRMER, 1930; VALLARTA, 1938; ROSSI, 1940). Unfortunately the computation of these cutoff rigidities is a formidable task even for the fastest computers in existence today since the general equation of particle motion in the magnetic field does not have a solution in closed form even in a simple dipole field. Therefore, to determine which rigidities are allowed at a specific geographical location, it is necessary to perform detailed and extensive numerical calculations of cosmic-ray trajectories in a mathematical model of the earth's magnetic field. To accurately determine the cutoff rigidity of a specific location on the earth in a specified direction, cosmic-ray trajectories are computed at successively lower rigidities until a rigidity is reached below which all particles are forbidden at that location.

The first demonstration that cosmic ray cutoff rigidities derived from realistic geomagnetic field models were superior to other geomagnetic parameters was shown in 1965 when the geomagnetic cutoff problem became tractable with computers. For over 30 years the cosmic ray intensity had been measured on various latitude surveys (CLAY, 1934; CLAY *et al.*, 1936; MILLIKAN and NEHER, 1935; COMPTON and TURNER, 1937; ROSE *et al.*, 1956; POMERANTZ and AGARWAL, 1962). For these surveys a cosmic radiation detector was usually mounted on a ship or aircraft and the cosmic radiation intensity was measured as a function of position. As the detector was moved from equatorial locations toward polar latitudes the cosmic radiation intensity increased because of the decreased "shielding" of the geomagnetic field. As the detector exceeded magnetic latitudes above approximately 45° the measured cosmic ray intensity essentially became constant; this is the result of the "turn over" in the galactic cosmic ray spectrum at lower energies coupled with a relatively smaller yield of secondaries generated by these lower energy particles during their collision with the matter in the atmosphere. (See WEBBER and QUENBY (1959) and NAGASHIMA *et al.* (1989) for a discussion of the cosmic ray spectrum and specified yield functions.) The inflection point on a plot of cosmic ray intensity vs latitude was called the "knee" of the latitude curve.

There was, however, one particular latitude survey for which the latitude curve

appeared to be anomalous (KODAMA, 1960) primarily because the "knee" was found to be at higher cutoff rigidities than detected on surveys in other regions of the world. Figure 1 illustrates these cosmic ray measurements made by a neutron monitor on a voyage of the Japanese ship SOYA near South Africa. The intensity has been plotted against the vertical cutoff rigidity as determined by three different methods:

- a) From the Störmer equation which used centered dipole coordinates;

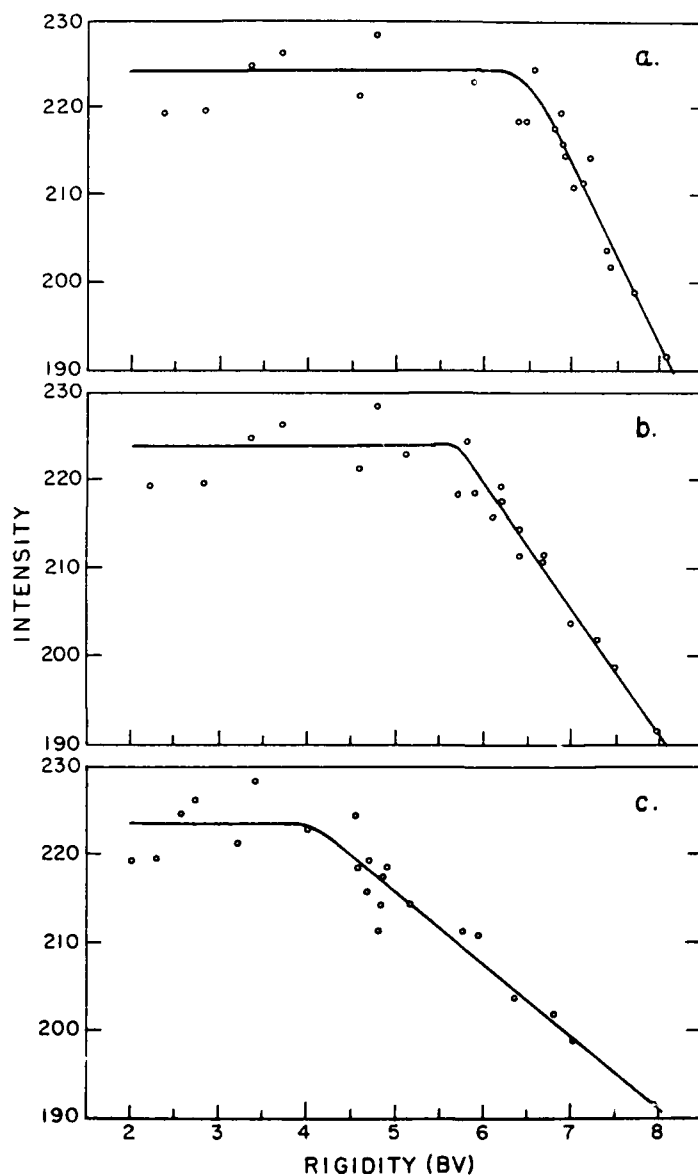


Fig. 1. Cosmic ray intensity from the 1956-1957 Soya voyage versus (a) the Störmer vertical cutoff rigidities, (b) the Quenby and Wenk vertical cutoff rigidities, and (c) the vertical cutoff rigidities calculated from the particle-tracing trajectory method.

b) From the QUENBY and WENK (1962) values which were derived from an empirical model; and

c) From trajectory calculations using the FINCH and LEATON (1957) geomagnetic field coefficients determined for Epoch 1955.

The "knee" of the latitude curve, located between a rigidity value of 2 and 3 GV as measured by surveys in other regions of the world, appeared to be located at a value of 6.3 GV using the Störmer derived rigidity values, at a value of 5.6 GV using the Quenby and Wenk derived values, and at a value of 4.0 GV using the trajectory-derived values (SHEA *et al.*, 1965). By using these trajectory-derived vertical cutoff rigidity values it was shown that the knee of the cosmic ray latitude curve as measured by this Japanese survey was located at a cutoff rigidity value somewhat more consistent with similar measurements in other regions of the world. From these results SHEA *et al.* (1965) concluded that the trajectory-tracing method for determining cutoff rigidities was superior to methods used previously.

3. Expansion of Trajectory-Derived Cutoff Rigidity Calculations

Encouraged by these results, and having the availability of a high speed digital computer, SHEA and SMART (1967) proceeded to calculate a world grid of trajectory-derived vertical cutoff rigidities each 15 degrees in latitude and longitude using the Finch and Leaton field model. Using an interpolation method based upon the MCILWAIN (1961) *L*-parameter, cutoff rigidities were interpolated from this world grid for the cosmic radiation intensity data measured by the neutron monitor flown on the project Magnet flights between 1958 and 1960 (POMERANTZ and AGARWAL, 1962). The cosmic ray intensity data were then plotted against the vertical cutoff rigidity values determined from the Quenby and Wenk world grid and those determined from the trajectory-derived world grid. As shown in Fig. 2, the cosmic radiation data were more compactly ordered using the trajectory-derived cutoff rigidity values although there was still an unsatisfying amount of scatter in the various data points.

SHEA *et al.* (1968) extended their vertical cutoff rigidity calculations to a world grid 5 degrees in latitude and 15 degrees in longitude, these values being used to derive an iso-rigidity contour map for Epoch 1955 as illustrated in the top half of Fig. 3. These trajectory-derived values then became the internationally accepted standard for vertical cutoff rigidities; unfortunately they are still being used with contemporary data which constitutes an abuse in the use of geomagnetic field models for geophysical analyses.

As time progressed the International Geomagnetic Reference Field for 1965 was developed (IAGA COMMISSION 2, WORKING GROUP 4, 1969) and the world grid of vertical cutoff rigidities was re-calculated using this internal field model (SHEA and SMART, 1975). Scientists in the cosmic ray community who utilized these models for various analyses felt that this far superior geomagnetic field model would be a final solution to the cutoff rigidity problem and that scatter in the cosmic ray data would be considerably reduced. With all of these theoretical solutions to the problem there are always experimenters around to test the theory; fortunately most of the experimental data exhibited less scatter when analyzed using the newer cutoff rigidity values.

However, there was one particular data set that seemed to indicate that the community simply didn't understand how to use the geomagnetic field model as a "tool" to resolve apparent discrepancies in the data sets. These data, plotted in the top part of

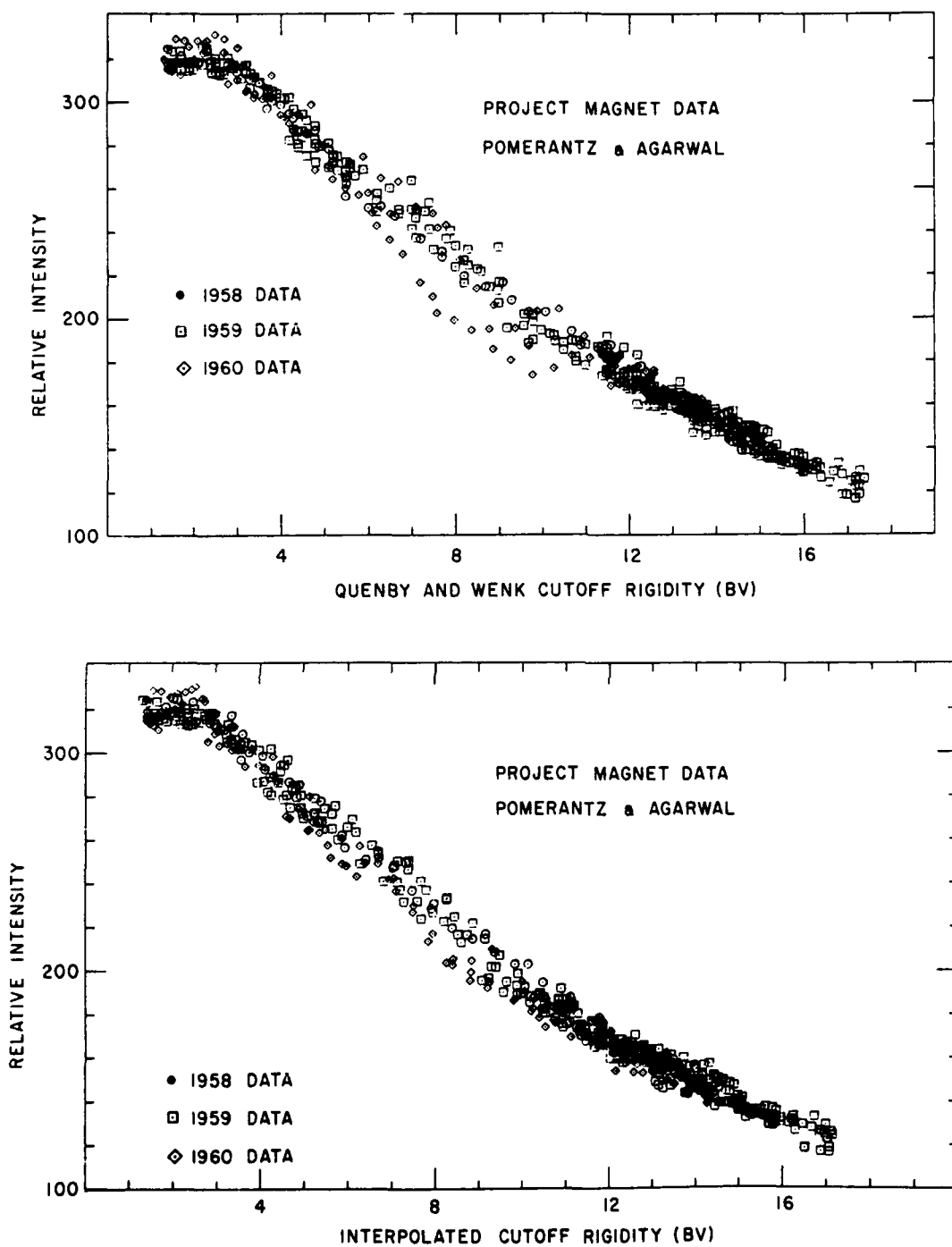


Fig. 2. Cosmic ray intensity data of project MAGNET ordered by both the Quenby and Wenk cutoff rigidities (top) and cutoff rigidities interpolated from the grid of trajectory-derived values (bottom).

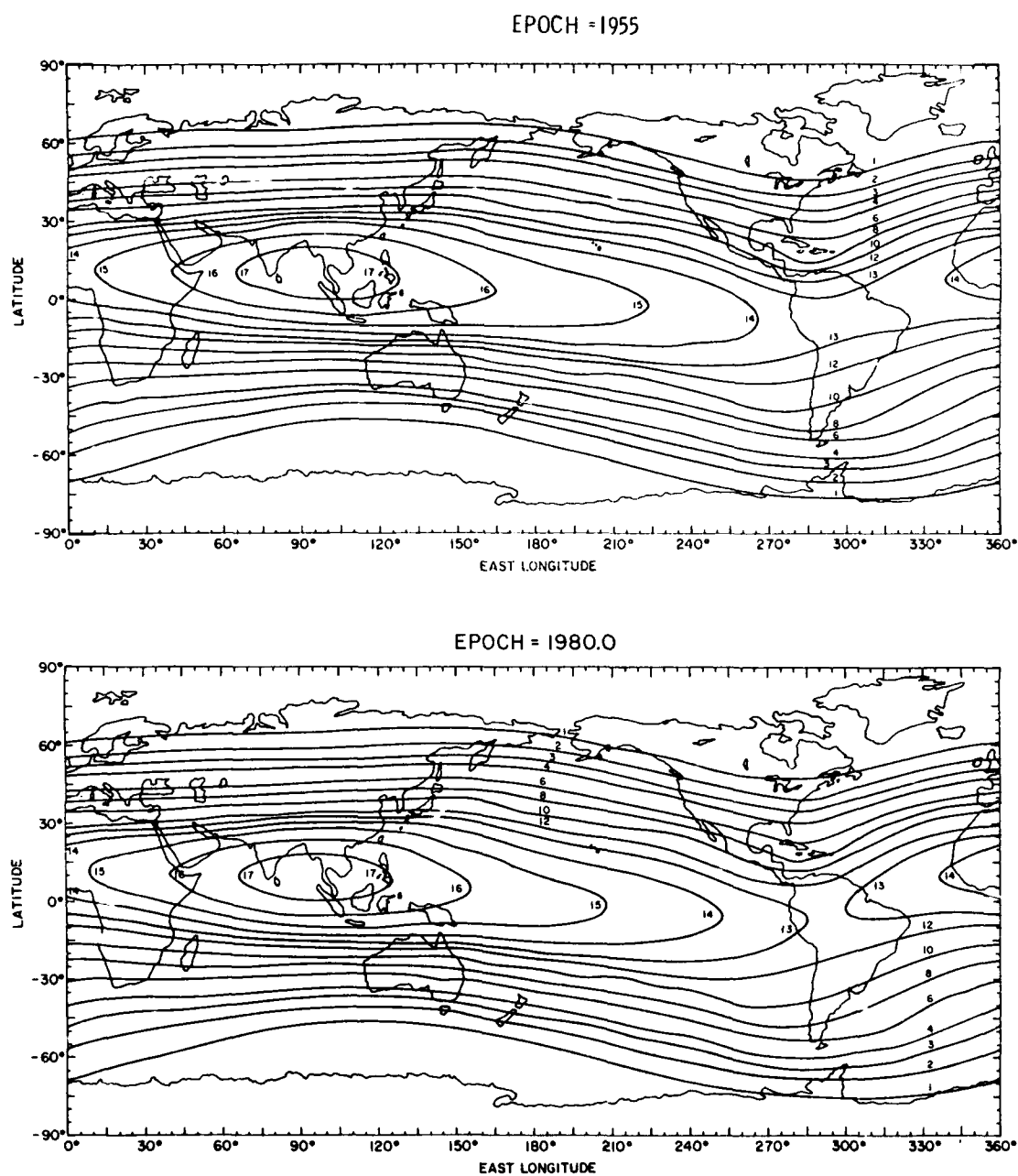


Fig. 3. Contours of vertical cutoff rigidities (in units of GV) as calculated using the Finch and Leaton magnetic field coefficients for Epoch 1955 (top). Contours of vertical cutoff rigidities as calculated using the International Geomagnetic Reference Field for Epoch 1980 (bottom).

Fig. 4, were obtained in October 1976 on a flight from Johannesburg, South Africa to New York City, U.S.A. (KÖNIG and STOKER, 1981). After making all known corrections to the experimental data, the cosmic ray intensity in the northern hemisphere appeared to be lower than the cosmic ray intensity in the southern hemisphere for locations having the same vertical cutoff rigidity as calculated using the IGRF Epoch 1965 model. Since the community generally had confidence in the trajectory calculations and the derived cutoff rigidity values it was felt that something must be wrong with the geomagnetic field model or the use of the model for cosmic radiation analyses.

4. Consideration of Secular Changes in the Geomagnetic Field

It was about this time that cosmic ray physicists utilizing geomagnetic field models started to attend the IAGA meetings, primarily in a desperate attempt to learn about field modeling. With their attendance at these meetings came the gradual understanding that these geomagnetic field models were more than just a description of the earth's magnetic field—they were actually describing the time evolution of the geomagnetic field since each model was determined for a particular epoch. The cosmic ray community had readily acknowledged the fact that the geomagnetic field was gradually evolving; however, it was genuinely felt that with the high energy cosmic ray particles being studied (>450 MeV) and the fact that geomagnetic changes took aeons, any field changes would result in just another "bump and wiggle" over the 30 years of our data base.

To ascertain the effect of the changing geomagnetic field on cosmic ray cutoff rigidity values, we calculated the location of the cosmic ray equator using field models for epochs 1955, 1965, 1975 and 1980 (SHEA and SMART, 1975; SHEA *et al.*, 1983). (A position along the cosmic ray equator is defined as the location of the minimum cosmic ray intensity along a geographic longitude. This should correspond to the maximum cutoff rigidity value along the same longitude. The loci of these points for all longitudes constitutes the cosmic ray equator.) As illustrated in Fig. 5 there was a considerable difference in the location of the cosmic ray equator for longitudes between 270° E and 360° E in the South American and Atlantic Ocean area between 1955 and 1980. These changes in the location of the cosmic ray equator are sufficiently significant that they have been experimentally measured (SPORRE and POMERANTZ, 1970; VAN DER WALT and STOKER, 1990). Thus the previous notion that the secular change in the geomagnetic field over a period of a few years would not significantly affect the measurement of high energy cosmic radiation at the earth was found to be invalid.

With the unexpected results pertaining to the cosmic ray equator differences we started seriously considering the concept of secular changes of the geomagnetic field and the effect these changes would have on cosmic ray analyses using data acquired over several decades. Using the International Geomagnetic Reference Field model for Epoch 1980 (IAGA DIVISION I, WORKING GROUP I, 1981; PEDDIE, 1982), we calculated a new world grid of vertical cutoff rigidities (SHEA and SMART, 1983). From this we derived another map of iso-rigidity contours, as shown in the bottom half of Fig. 3, and compared these contours with those determined for Epoch 1955. From a casual inspection the two maps appear to be similar; however, closer scrutiny reveals several differences, the most notable being that the 13 GV rigidity contours extend across both northern and southern magnetic hemispheres for Epoch 1955 but do not extend around the world for Epoch 1980.

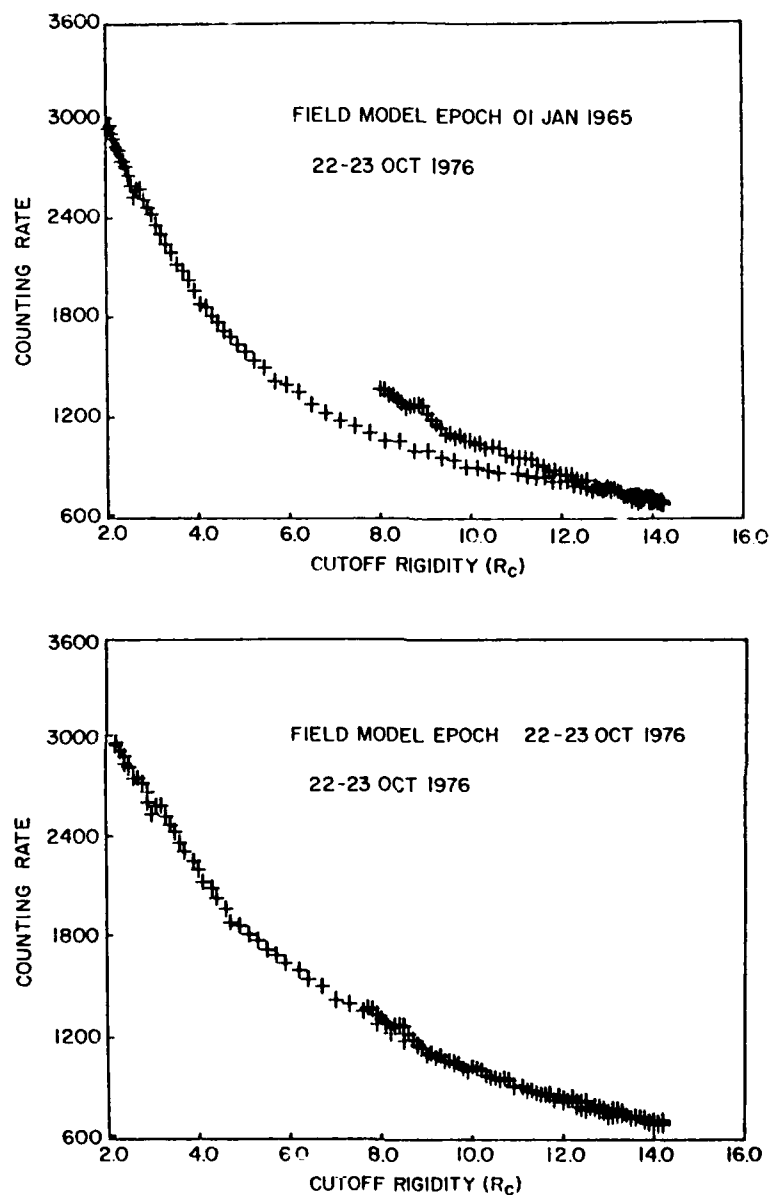


Fig. 4. Cosmic ray intensity data obtained on an airline flight between South Africa and New York City in October 1976 as plotted against vertical cutoff rigidities calculated using the 1965.0 geomagnetic field model (top) and against vertical cutoff rigidities appropriate for October 1976 (bottom). The "upper" section of the curve (between 8 and 12 GV) in the top panel are the intensity data obtained in the southern hemisphere between South Africa and the equatorial region; the "lower" section of the curve are the intensity data obtained in the northern hemisphere between the equatorial region and New York City.

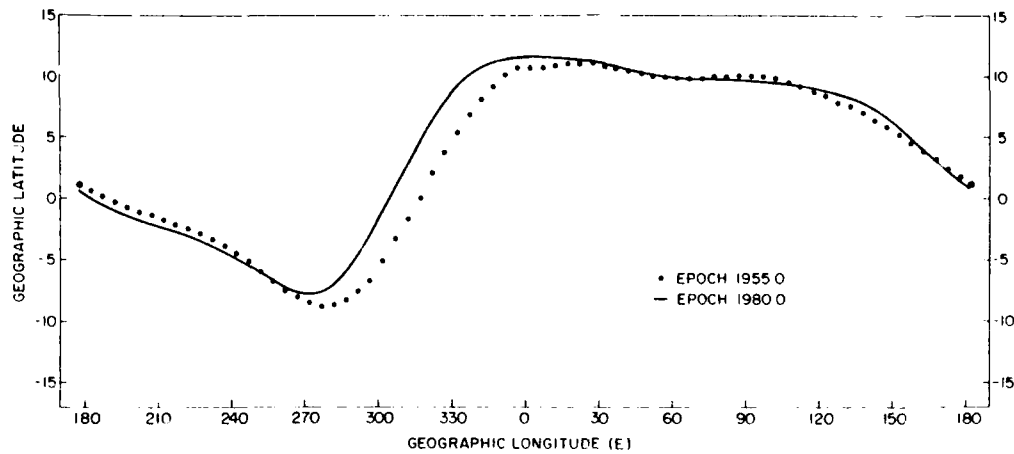


Fig. 5. Location of the cosmic ray equator as calculated using the Finch and Leaton geomagnetic field model for epoch 1955 (dots) and the International Geomagnetic Reference Field for epoch 1980 (solid line).

When we determined the differences in cutoff rigidities for various epochs on a location by location basis, we found, to our absolute horror, that in some regions of the world, specifically the North Atlantic Ocean, the secular change was more than 1% per year as illustrated in Fig. 6. In other regions of the world, such as over Australia, the cutoff rigidities remained essentially constant. Changes of 1% per year are extremely significant to a community who is trying for a measurement stability better than 1% over an entire 30-year interval.

Geomagnetic field modelers will undoubtedly recognize that the effect in the North Atlantic is the "well-known" westward drift. This "well-known" westward drift might be very well known to the geomagnetic community; unfortunately, most of the cosmic ray community doesn't even have a passing acquaintance with this physical phenomenon. The steady westward increase in the cosmic ray cutoff rigidity values off the North Atlantic coast is starting to affect the measurements by the internationally accepted standard neutron monitors of Deep River, Canada, and Mt. Washington, U.S.A. The cutoff rigidity for these two stations was 1.02 GV and 1.24 GV, respectively, for Epoch 1955 and 1.02 GV and 1.28 GV, respectively, for Epoch 1965; however, these values increased to 1.14 GV and 1.46 GV for Epoch 1980 (SHEA *et al.*, 1990) using the Definitive Geomagnetic Reference Field Model (IAGA DIVISION I, WORKING GROUP I, 1987).

With nonuniform secular changes in the vertical cutoff rigidities throughout the world, cosmic ray physicists must now determine if changing cutoff rigidities must be considered in their various analyses. As an example consider the data plotted in the top half of Fig. 4. When the flight path from Johannesburg to New York City is located on the map of secular change in the vertical cutoff rigidity we find that the aircraft went from a region of decreasing cutoff rigidity (Johannesburg) through a region of increasing cutoff rigidity (the North Atlantic); in fact the flight path, shown by the dashed black line in Fig. 6, went right through the region of 1% per year change in vertical cutoff rigidity. We again determined the vertical cutoff rigidity for the flight path—but this time we used a geomagnetic field model appropriate for the month of the aircraft flight. When these

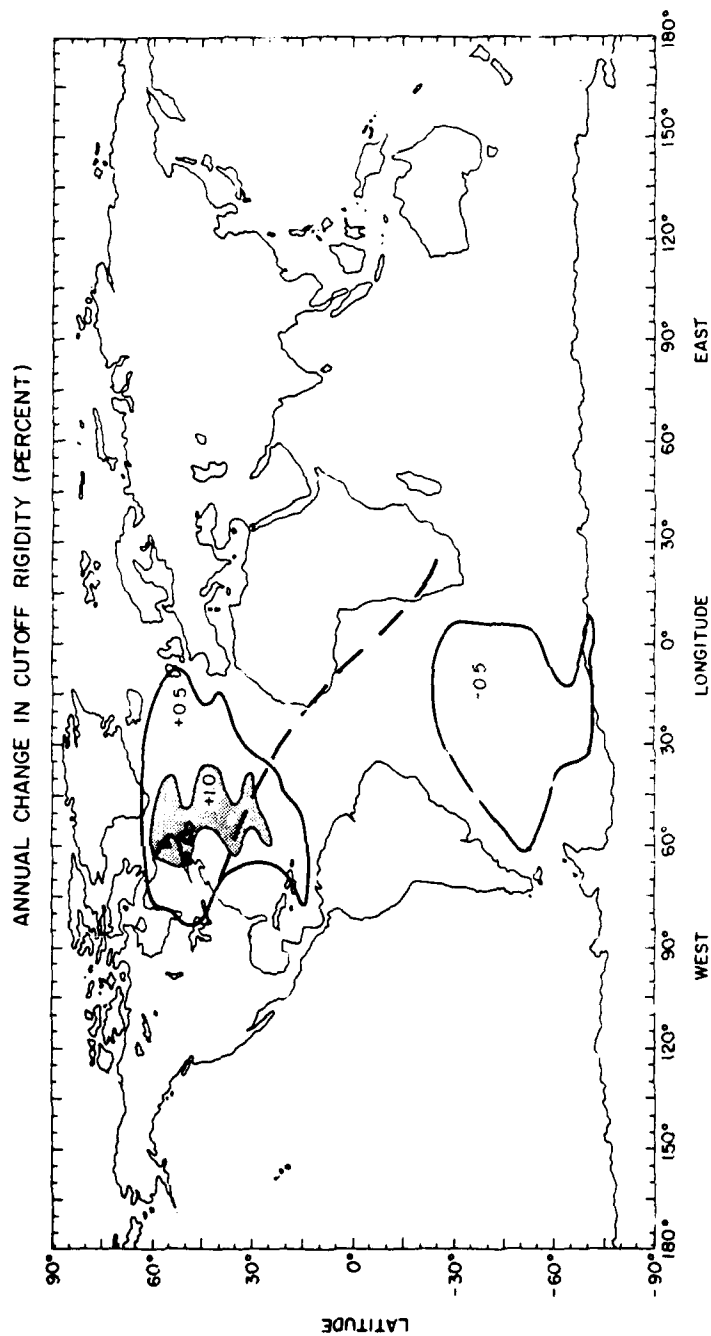


Fig. 6. Contours of averaged annual change of vertical cutoff rigidities between 1965.0 and 1983.0. The dashed line indicates the route of the airline flight between South Africa and New York City in October 1976.

more appropriate cutoff rigidity values are used to order the cosmic ray intensity measurements, as illustrated in the bottom part of Fig. 4, we find that the previous discrepancy has been resolved and that the cosmic ray intensity, measured at equivalent cutoff rigidities, is the same in both hemispheres.

5. Long Term Galactic Cosmic Ray Measurements

Cosmic ray latitude surveys are not the only use cosmic ray physicists have for the geomagnetic field models. Another interesting cosmic ray problem is the determination of the galactic cosmic ray spectrum at each solar minimum and the galactic cosmic ray modulation over the various solar cycles. Since the galactic cosmic ray intensity is at a maximum near the minimum in the sunspot cycle, a cosmic ray spectrum is usually determined at solar minimum and compared with the galactic cosmic ray spectrum derived at the previous solar minimum. These measurements are used for long term evaluations of the galactic cosmic radiation and the propagation of these high energy particles in the heliosphere. If the long term measurements are taken at a location where the cutoff rigidity is stable, we can determine the background galactic cosmic radiation intensity for successive solar minima.

There have been a number of neutron monitors operating for many years at relatively high latitudes, e.g. Mt. Washington, Deep River, Oulu, Finland, Thule, Greenland and Climax, U.S.A. These stations can be used to determine the cosmic ray spectrum down to relatively low energies. The vertical cutoff rigidity at Climax was calculated to be extremely stable with values of 3.03 GV and 2.99 GV for Epochs 1955 and 1980 respectively, and as shown in Fig. 7, the cosmic ray intensity reaches approximately the same value during the solar minimum of 1954, 1965, and 1987. (The slightly lower value in 1976 has been attributed (SHEA and SMART, 1990) to excessive turbulence in the interplanetary medium throughout solar minimum.)

To determine the high energy portion of the cosmic ray spectrum a station in the equatorial regions is required. Unfortunately the station with the longest history of operation is located in Huancayo, Peru where the vertical cutoff rigidity has decreased from 13.45 GV in 1955 to 12.91 GV in 1980. Figure 8 shows the galactic cosmic ray intensity recorded by the Huancayo neutron monitor prior to any correction for the decrease in the geomagnetic field over the 35-year period. A decreasing cutoff rigidity implies an increase in galactic cosmic ray intensity observed at this location (everything else being equal), and indeed, this is the effect observed at Huancayo (COOPER and SIMPSON, 1979). Efforts are now underway to correct these cosmic ray intensity values for the changes in the geomagnetic field employing vertical cutoff rigidities calculated using the newly derived Definitive Geomagnetic Field Coefficients extending back to 1945 (IAGA DIVISION I, WORKING GROUP I, 1987).

6. Other Cosmic Ray Studies Requiring Accurate Geomagnetic Field Models

In addition to cosmic ray latitude surveys and galactic cosmic ray spectrum and modulation studies, an accurate representation of the geomagnetic field is required for many other cosmic ray investigations. For example, the study of relativistic solar particle events, particularly in trying to deconvolve the anisotropies and solar particle spectrum, requires an accurate geomagnetic field model to determine the asymptotic direction of

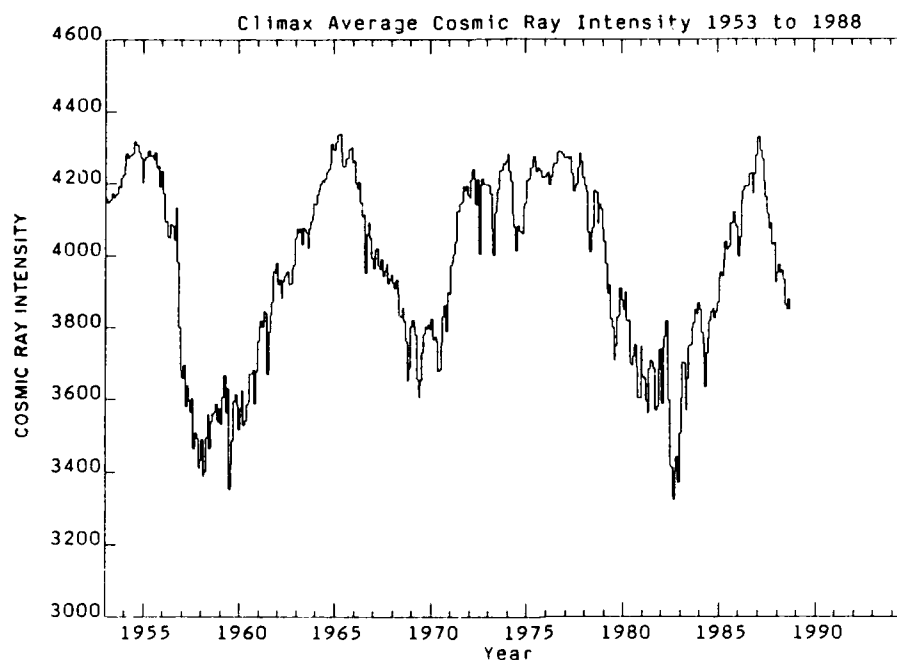


Fig. 7. Cosmic ray intensity as measured by the Climax, Colorado neutron monitor between 1965 and 1987. No geomagnetic correction has been applied since the cutoff rigidity remained essentially the same throughout this period.

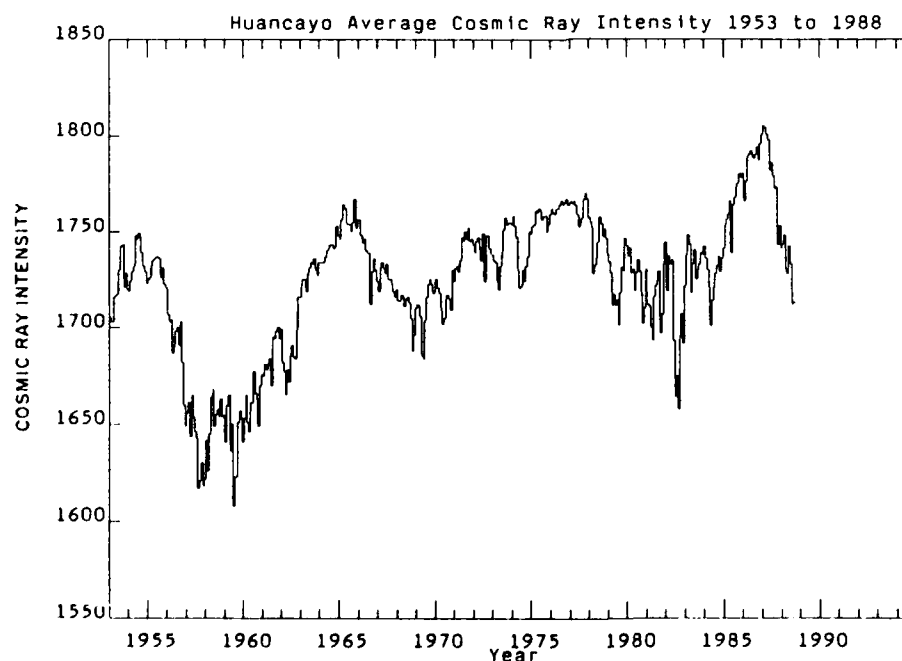


Fig. 8. Cosmic ray intensity as measured by the Huancayo neutron monitor between 1954 and 1987 without correction for geomagnetic cutoff rigidity changes.

approach for particles with specific rigidities for each of the stations recording the increase. The analysis has become extremely sophisticated with increasing reliability found when combining an internal field model with a time dependent model of the magnetosphere to model the current systems (FLÜCKIGER and KOBEL, 1990). These effects are particularly important for high latitude neutron monitors which typically record the largest increases.

Solar particle spectra are usually much "softer" than the galactic cosmic radiation spectrum; therefore high latitude neutron monitors with relatively low cutoff rigidities (between 1 and 3 GV) may record significant increases during these relativistic solar particle events. For this reason, accurate cutoff rigidities should be used in analyzing these events, especially when comparing the increases recorded at different stations.

The determination of the cutoff rigidity at satellite altitudes has also been used to discriminate the charge state of cosmic ray particles with surprising results that some of the incoming particles are not completely stripped of electrons (MITRA *et al.*, 1989). Other cosmic ray experimenters, particularly those investigating isotopic composition, have used the geomagnetic cutoff rigidity to locate the first penumbral band for balloon and spacecraft measurements (LUND and SORGEN, 1977; SOUTOUL *et al.*, 1981).

7. Summary

We have summarized how the geomagnetic field is used to calculate cosmic ray vertical cutoff rigidities, and how these values are used as an ordering parameter for different cosmic radiation investigations. Studies such as latitude surveys, long term modulation, and relativistic solar particle increases, are particularly sensitive to the vertical cutoff rigidity, and care must be taken in analyzing cosmic radiation measurements obtained in regions of the world where the secular variations in the geomagnetic field result in significant changes in the geomagnetic cutoff rigidities.

This has been a discussion of how the geomagnetic field models have been used, and, yes, abused, by cosmic ray physicists. Without a doubt the geomagnetic field models have greatly aided our understanding of cosmic radiation over the past half century. In turn, as a community, we have been forced to learn more about the field models and their derivation than originally thought necessary. We now realize that we can attribute some of the apparent discrepancies in cosmic radiation data to geomagnetic effects. We eagerly hope for the day that the geomagnetic modelers can provide us with a geomagnetic field model that will completely resolve all of our geomagnetic problems leaving us with one less parameter to consider in the analysis of cosmic radiation.

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